Prepared for ASME Symposium, Philadelphia, Pa., Nov. 17-22, 1963

(NASA TM X-51111)

19p

N65-89007

~~X64 10803~~

Code 2A

E-2187

THERMAL CONDUCTANCE OF MOLYBDENUM AND STAINLESS STEEL 304 INTERFACES IN A VACUUM

By R. D. Sommers and W. D. Coles

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

[1963] 19p refs Presented at the ASME Symp., Philadelphia, 17-22 Nov. 1963

INTRODUCTION

□ Cat

In recent years there has been a revival of interest in the thermal conductance of metallic contacts. The advent of the space age has in particular stimulated an interest in the thermal conductance of metallic contacts in a vacuum environment. This paper reports a series of measurements made on interfaces composed of molybdenum and stainless steel 304 surfaces in a vacuum of 10^{-6} Torr.

When two metallic surfaces are placed in contact, they do not touch each other over the entire apparent area of contact because of the microscopic irregularities of the surfaces.

The heat transfer across the interface will occur in the following modes:

(1) Metallic conduction

(2) Conduction through the material in voids, if any

(3) Radiation

In a vacuum environment the second mode will essentially be eliminated, and it is evident that the thermal conductance will largely be determined by the extent of real metallic contact present. In most cases the amount of actual contact is a very small fraction of the apparent area of contact.

Application of pressure to the interface will cause deformation of the microscopic irregularities, or asperities, and result in an increase in the fraction of real contact. The thermal conductance will thereby increase with increasing surface loading.

EXPERIMENTAL PROCEDURE

This paper concerns an experimental investigation of the thermal conductance of molybdenum and stainless steel interfaces over ranges of interface temperature from 200° to 1100° F and interface contact pressure from 80 to 800 psi in a vacuum of 10^{-6} Torr.

The experimental apparatus is shown in Figs. 1 to 3. Thermal energy is supplied by means of induction heating to the heater head shown in Fig. 1. The heat flows along the cylindrical test shaft, across the test interface, and through the copper heat-flow meter and is removed by either air or water cooling at the bottom.

The magnitude of the heat flow is determined by measuring the temperature gradient along the copper heat-flow meter. The heat-flow meter is a length of high-purity, oxygen-free copper for which the thermal conductivity is known. The thermal conductivity values used were taken from [1][1] and are presented in Fig. 4.

The temperatures of the surfaces comprising the test interface are obtained by measuring the temperatures on either side of the test interface and extrapolating these temperatures to the appropriate surface.

[1]Numbers in brackets designate References at end of paper.

The thermal conductance is calculated according to the following definition of the conductance:

$$h = \frac{\dot{q}/A}{\Delta T_i}$$

where h is the thermal conductance, $\dot{q}$ is the heat-flow rate, A is the apparent contact area, and ΔT_i is the temperature drop across the interface. The interface contact pressure is provided by loading of the test shaft from outside the vacuum region with the air cylinder shown in Fig. 1. The contact pressure is determined by measuring the loading force with a load cell placed between the air cylinder and the test shaft extension as shown in Fig. 1.

During the course of the investigation, it was discovered that the O-ring seals around the test shaft extension, where it passed through the vacuum bell jar, were capable of exerting a fairly large frictional force along the axis of the test shaft. This O-ring friction was quite capable of supporting a load of 45 lb. A 45-lb load on the test shaft corresponds to an interface contact pressure of about 70 psi. Since the load measuring system, that is, the load cell, was not between the O-ring seals and the test interface, the O-ring friction was capable of introducing a ±70 psi uncertainty into the interface contact-pressure measurement. This situation was remedied by providing a "friction reliever" in the form of a pulsed hammer that applied two sharp blows to the test shaft extension every 30 sec. This action proved sufficient to relieve the O-ring residual forces nearly completely.

Four contacts are investigated involving four combinations of surfaces, two molybdenum surfaces, Mo_1 and Mo_2, and two stainless steel 304 surfaces, SS_1 and SS_2. The characteristics of the various surfaces and combinations are presented in Table 1.

The measurements for any particular interface were taken in the following sequence. Beginning at the lowest temperature, the lowest pressure was applied to the interface. Measurements were made at time intervals until an equilibrium situation was attained, at which time the contact pressure was raised to the next higher value while approximately the same average interface temperature was maintained. When the highest pressure had been reached, the temperature was raised and the measurements were taken through a decreasing sequence of contact pressure. The increasing and decreasing cycle of contact pressure, with temperature changes occurring at the contact-pressure extremes, was repeated until the highest temperatures had been reached.

An equilibrium condition was considered to have been attained when the measured temperatures exhibited a change of less than 1° or 2° F over two or three measurement intervals. Measurement intervals were of 3- or 4-hr duration.

A period of up to 12 hr was required to reach an equilibrium condition depending on whether a contact-pressure change or a temperature change had been effected. After a contact-pressure change, conditions leveled out in a time period of 5 to 6 hr. A change of temperature required the 12-hr period for equilibrium to occur.

The thermal conductance data are presented in Tables 2 to 5 and Figs. 5 to 8.

DISCUSSION OF RESULTS

One of the most important factors governing the thermal conductance of any particular interface is the interface contact pressure. This is not surprising since, for any particular pair of surfaces, the contact pressure will to a large degree determine the extent to which the surfaces make "real" contact.

The effect of surface material can be seen by comparing Figs. 5 and 6 for the molybdenum-molybdenum and SS 304 - SS 304 interfaces. The molybdenum interface displays a much higher thermal conductance than does the stainless steel interface at comparable contact pressures. The difference between the thermal conductance of the molybdenum interface and the stainless steel interface, approximately a factor of 5, is about the same difference that exists between the thermal conductivities of the two metals, which indicates that metallic conduction is perhaps the dominant mode of heat transfer. As further evidence for the domination of metallic conduction, Fig. 5 for the SS 304 - SS 304 interface presents the thermal conductance for radiation only. This curve was obtained by separating the surface approximately 1/16 in. and measuring the heat flow across the resulting gap. From Fig. 5 it is quite evident that the thermal conductance for radiation is very small compared to the thermal conductance when the surfaces are in contact.

The thermal conductance of the molybdenum-molybdenum and SS 304 - SS 304 interfaces tends to increase with increasing interface temperature. The effect of contact pressure is more pronounced at the higher interface temperatures. Both of these effects are felt to be associated with the decline of material strength at higher temperatures.

Loss of material strength calls for an increase in "real" area of contact to support the applied load. An increase in "real" contact area has the effect of increasing the interface thermal conductance.

In view of the behavior of the one-metal interface configurations shown in Figs. 5 and 6, the behavior of the mixed-interface configurations represented in Figs. 7 and 8 is somewhat surprising.

Two contact combinations are illustrated in Figs. 7 and 8, in which the heat-flow directions and the surfaces comprising the interfaces are different. Both cases show a trend for the thermal conductance to decrease with increasing average interface temperature. For the molybdenum-steel interface this trend was reversed at the higher interface temperatures, whereas for the steel-molybdenum interface the decreasing trend continued to the highest temperatures attainable with the apparatus. It might be well to emphasize that the interface of Fig. 7 is not the same as the interface of Fig. 8 with just the heat-flow direction changed.

The reasons for the decreasing trend in the data shown in Figs. 7 and 8 are nebulous. Since the thermal conductance of an interface is a strong function of the manner in which the surfaces of the interface make contact, and since the behavior of the like interfaces gave no indication of the behavior of the mixed interfaces of Figs. 7 and 8, the explanation probably is connected somehow with the dissimilar natures of molybdenum and stainless steel 304.

It is of interest to note that Barzelay et al. [2] report the thermal conductance of some stainless steel 416 and aluminum joints. The thermal conductance tended to decrease with increasing average interface temperature. This effect was attributed by them to warping of the materials, particularly the SS 416, which severely affected the surface matching at the interface.

The overall configuration of the present test is similar to that of [2]. Qualitatively the results in the cases of molybdenum - SS 304 configurations in this experiment are similar to SS 416 - aluminum results of [2]. A tendency for the thermal conductance to decrease with increasing average interface temperature was observed in both cases. Further, the thermal conductance is lower when the heat flows from the stronger material to the weaker than when the heat flows from the weaker material to the stronger. This last effect is probably associated with the temperature dependence of the tensile strengths of the materials.

If warping of the stainless steel were the major cause of decreasing thermal conductance with increasing temperature, it would be expected that an interface composed of two stainless steel surfaces would also exhibit some tendency for the thermal conductance to decrease with increasing temperature. This was not the case for the stainless steel 416 interfaces of [2] or the stainless steel 304 interfaces of the present tests.

Even though stainless steel is common to the present investigation and that of [2], it is perhaps more significant that the mixed-interface configurations of the present tests and those of [2] involved two materials of very different physical properties.

The tendency of the thermal conductance to decrease with increasing temperature in the mixed-interface configurations could, perhaps, be due to a reduction in the number of contact sites brought about by the different reactions of the surface materials to temperature changes.

REFERENCES

1. C. F. Lucks and H. W. Deem, "Thermal Properties of 13 Metals," Am. Soc. for Testing Materials, Special Tech. Pub. 227.

2. M. E. Barzelay, Win Nee Tong, G. F. Holloway, "Effect of Pressure on Thermal Conductance of Contact Joints," NACA TN 3295.

E-2187

TABLE 1. - SURFACE AND INTERFACE CHARACTERISTICS

(a) Surface characteristics

Surface	Material	Surface roughness, μ in.	Surface area, sq in.
Mo_1	Molybdenum	16	0.6207
Mo_2	Molybdenum	↓	.8012
SS_1	SS 304	↓	.6940
SS_2	SS 304	↓	.7850

(b) Interface characteristics

Configuration	Heat-flow direction	Apparent contact area, sq in.
SS_1-SS_2	SS_1 to SS_2	0.6940
SS_1-Mo_2	SS_1 to Mo_2	.7353
Mo_1-Mo_2	Mo_1 to Mo_2	.6207
Mo_1-SS_2	Mo_1 to SS_2	.6207

TABLE 2. - THERMAL CONDUCTANCE DATA FOR STAINLESS STEEL 304 - STAINLESS STEEL 304 INTERFACE

[Ambient pressure, 10^{-6} Torr; surface roughness, 16 μ in.]

Contact pressure, psi	Heat flow, $\dot{q}/A$, Btu/(hr)(sq ft)	Surface temperature, T_1, °F	Surface temperature, T_2, °F	Interface temperature difference, ΔT_i, °F	Average interface temperature, T_i, °F	Interface conductance, h, Btu/(hr)(sq ft)(°F)
765	29,100	402	305	97	353	300
	43,450	483	347	136	415	319
	42,900	523	397	126	460	340
	60,600	695	523	172	609	352
	71,800	799	605	194	702	370
	86,400	900	700	200	800	432
	89,100	941	726	215	834	414
380	23,600	453	280	173	367	136
	27,350	518	313	205	415	133
	37,120	603	375	228	489	163
	38,270	654	413	241	533	159
	60,400	827	512	315	670	192
	63,450	893	590	303	740	209
	75,400	1004	648	356	826	212
	85,800	1065	700	365	883	235
220	20,200	490	240	250	365	81
	32,350	659	348	311	504	104
	44,670	866	474	392	670	114
	55,100	981	544	437	763	126
	75,200	1152	601	551	876	136
	80,400	1179	628	551	903	146
	83,700	1207	662	545	939	154

TABLE 2. - Concluded. THERMAL CONDUCTANCE DATA FOR STAINLESS STEEL 304 - STAINLESS STEEL 304 INTERFACE

[Ambient pressure, 10^{-6} Torr; surface roughness, 16 μ in.]

Contact pressure, psi	Heat flow, $\dot{q}/A$, Btu/(hr)(sq ft)	Surface temperature, T_1, °F	Surface temperature, T_2, °F	Interface temperature difference, ΔT_i, °F	Average interface temperature, T_i, °F	Interface conductance, h, Btu/(hr)(sq ft)(°F)
80	9,220	582	154	428	368	21.5
↓	14,340	598	190	408	394	35.1
	19,390	777	247	530	512	36.5
	25,200	904	302	602	603	41.9
	29,220	1021	344	677	683	43.2
	40,480	1061	455	606	758	66.8
	45,850	1326	491	835	908	55.0
No contact, surfaces separated by 1/16 in.	2,308	671	90	581	381	3.97
	2,820	770	96	673	483	4.19
	6,505	1004	138	866	571	7.51
	6,880	1195	146	1049	670	6.56
	9,660	1302	170	1132	736	8.54

TABLE 3. - THERMAL CONDUCTANCE DATA FOR MOLYBDENUM - STAINLESS STEEL 304 INTERFACE

[Heat flow from Mo to SS 304; ambient pressure 10^{-6} Torr; surface roughness, 16 μ in.]

Contact pressure, psi	Heat flow, $\dot{q}/A$, Btu/(hr)(sq ft)	Surface temperature, T_1, °F	Surface temperature, T_2, °F	Interface temperature difference, ΔT_i, °F	Average interface temperature, T_i, °F	Interface conductance, h, Btu/(hr)(sq ft)(°F)
765	16,900	330	162	168	246	100.5
	23,950	450	200	250	325	95.6
	35,400	692	251	441	472	80.3
	40,700	822	302	520	562	78.3
	49,200	880	320	560	600	87.0
	62,000	1051	400	651	725	95.2
↓	75,200	1176	495	681	835	110.5
380	15,600	372	157	214	263	72.6
	21,050	488	187	301	338	69.8
	27,660	747	233	514	490	53.8
	32,750	870	269	601	569	54.5
	39,100	930	289	641	609	60.9
	46,800	1100	355	745	727	62.9
↓	58,400	1212	406	806	809	72.4
220	13,000	413	148	265	281	49.1
	16,900	535	177	358	356	47.3
	23,850	777	222	555	500	42.9
	26,900	900	250	650	575	41.5
	31,800	989	290	699	640	45.6
	38,000	1135	324	811	730	46.8
↓	47,000	1265	400	865	832	54.4
80	8,440	481	145	336	313	25.1
	16,450	821	208	613	515	26.8
	21,900	932	245	687	588	31.8
	25,720	1040	285	755	662	30.2
	23,000	1132	310	822	721	27.9
↓	34,100	1330	375	955	802	35.6

TABLE 4. - THERMAL CONDUCTANCE DATA FOR MOLYBDENUM - MOLYBDENUM INTERFACE

[Ambient pressure, 10^{-6} Torr; surface roughness, 16 μ in.]

Contact pressure, psi	Heat flow, q/A, Btu/(hr)(sq ft)	Surface temperature, T_1, °F	Surface temperature, T_2, °F	Interface temperature difference, ΔT_i, °F	Average interface temperature, T_i, °F	Interface conductance, h, Btu/(hr)(sq ft)(°F)
765	50,400	325	292	33	309	1,527
	75,000	444	394	50	419	1,500
	148,000	573	484	89	528	1,663
	105,400	573	517	56	545	1,882
	181,500	693	589	104	641	1,745
	219,700	792	690	102	741	2,152
	236,800	841	743	98	792	2,416
	256,520	916	800	116	858	2,211
	295,300	978	865	113	922	2,612
	338,000	1100	984	116	1042	2,915
380	28,780	247	212	35	230	822
	48,680	362	306	56	329	869
	71,800	484	402	82	443	875
	142,100	599	482	117	540	1,214
	100,400	606	510	96	560	1,045
	170,000	731	595	136	663	1,250
	205,100	854	690	164	772	1,252
	223,000	897	743	154	820	1,446
	245,300	955	781	174	868	1,411
	276,000	1024	850	174	947	1,585
	327,800	1135	965	170	1050	1,929

TABLE 4. - Concluded. THERMAL CONDUCTANCE DATA FOR MOLYBDENUM - MOLYBDENUM INTERFACE

[Ambient pressure, 10^{-6} Torr; surface roughness, 16 μ in.]

Contact pressure, psi	Heat flow, $\dot{q}/A$ Btu/(hr)(sq ft)	Surface temperature, T_1, °F	Surface temperature, T_2, °F	Interface temperature difference, ΔT_i, °F	Average interface temperature, T_i, °F	Interface conductance, h, Btu/(hr)(sq ft)(°F)
220	46,000	394	308	86	351	535
↓	69,800	524	408	116	466	601
	134,600	658	475	183	567	735
	95,400	654	510	144	582	662
	159,500	799	581	218	690	727
	191,400	891	667	224	779	854
	209,000	959	709	250	834	836
	227,200	1012	760	252	886	902
	256,200	1092	819	273	956	939
	299,600	1202	926	276	1064	1,085
80	22,300	317	160	157	238	142
↓	50,300	659	313	346	486	145
	96,100	900	344	556	622	168
	122,700	1149	457	692	803	177
	148,500	1396	566	830	981	179
	181,500	1542	656	886	1099	205

TABLE 5. - THERMAL CONDUCTANCE DATA FOR STAINLESS STEEL 304 - MOLYBDENUM INTERFACE

[Heat flow from SS 304 to Mo; ambient pressure, 10^{-6} Torr; surface roughness, 16 μ in.]

Contact pressure psi	Heat flow, $\dot{q}/A$ Btu/(hr)(sq ft)	Surface temperature, T_1, °F	Surface temperature, T_2, °F	Interface temperature difference, ΔT_i, °F	Average interface temperature, T_i, °F	Interface conductance, h, Btu/(hr)(sq ft)(°F)
765	40,240	301	244	57	273	706.0
	40,970	318	261	56	289	731.0
	52,990	385	304	80	345	658.0
	57,200	402	317	84	359	680.0
	74,740	524	400	124	462	602.0
	93,380	694	496	198	595	472.0
	105,691	770	540	230	655	460.0
	121,820	1014	650	364	832	335.0
	122,140	1113	675	438	894	279.0
380	33,450	364	274	90	319	371.0
	49,250	461	335	126	398	391.0
	66,790	591	411	180	503	370.0
	84,990	769	505	264	637	321.0
	97,840	840	560	280	700	350.0
	114,410	1056	633	423	847	270.0
	103,560	1201	687	514	944	201.0
220	28,730	396	280	116	343	247.0
	44,950	517	354	163	435	275.0
	59,600	670	447	223	559	267.0
	77,580	835	530	305	682	254.0
	90,000	922	594	328	758	276.0
	105,140	1100	630	470	865	223.0
	97,950	1223	698	525	960	186.0
80	50,450	854	488	366	671	137.0
	56,000	1105	620	485	862	115.0
	63,410	1253	735	518	994	122.0

E-2187

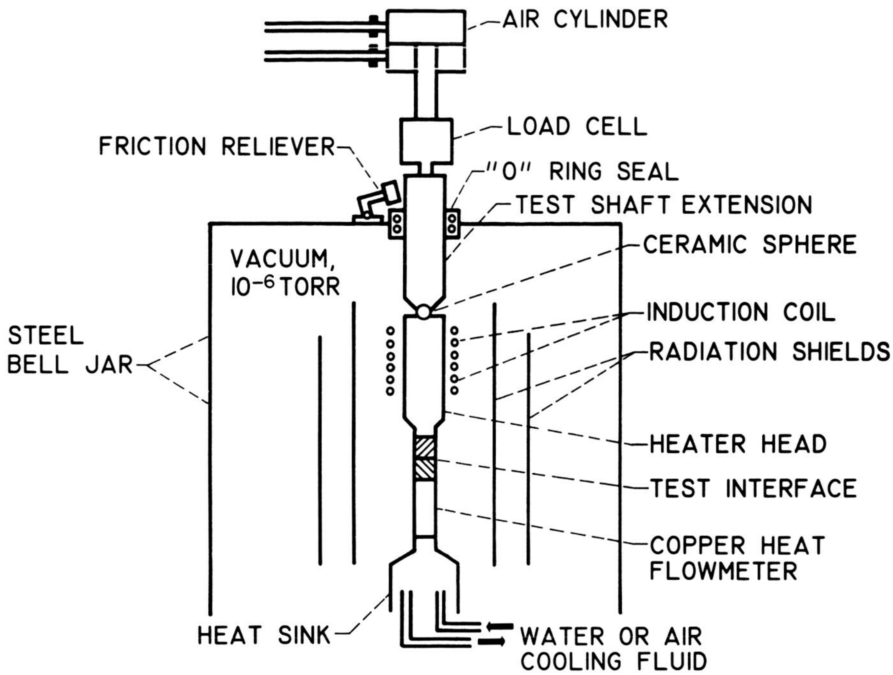

Fig. 1. - Thermal conductance apparatus.

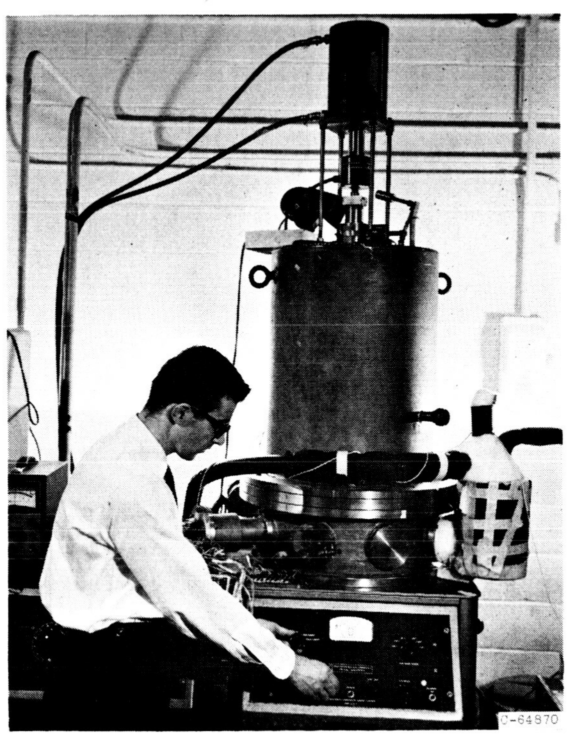

Fig. 2. - Thermal conductance apparatus, external view.

E-2187

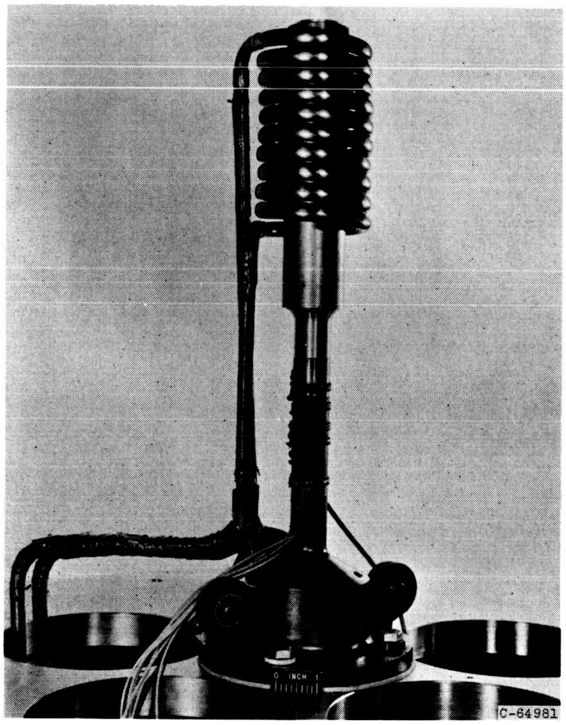

Fig. 3. - Thermal conductance apparatus, view of test section.

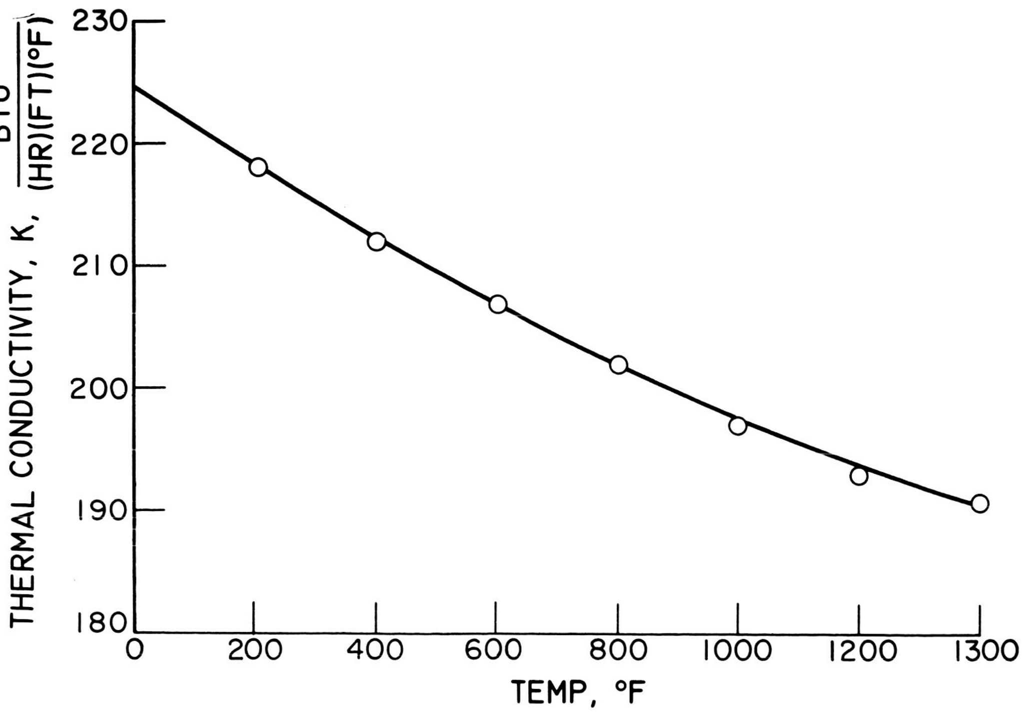

Fig. 4. - Thermal conductivity of copper (ref. 1).

E-2187

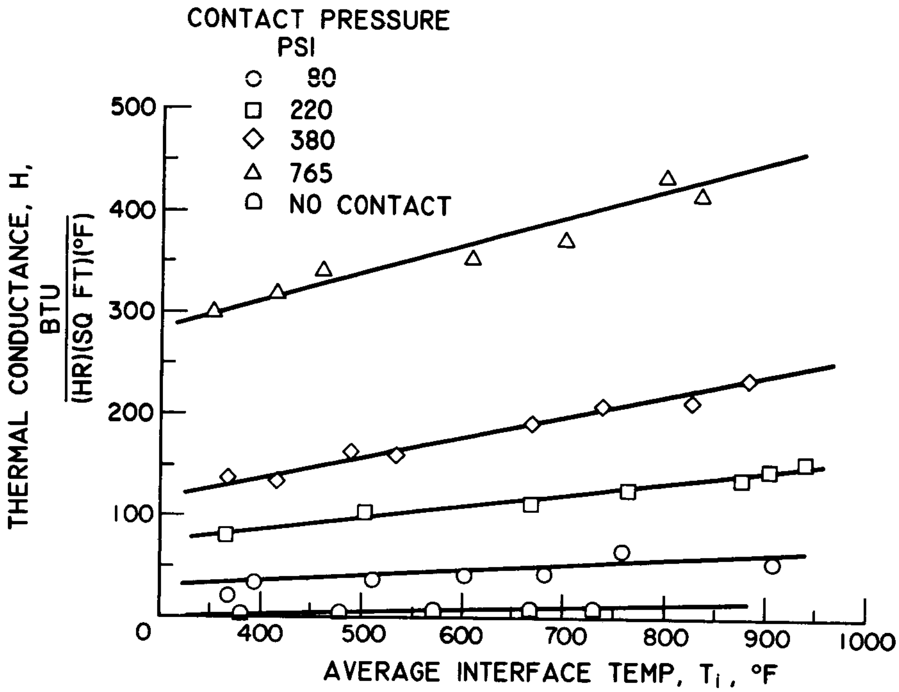

Fig. 5. - Thermal conductance of stainless steel 304-stainless steel 304. Ambient pressure, 10^{-6} Torr; surface roughness, 16 μin.

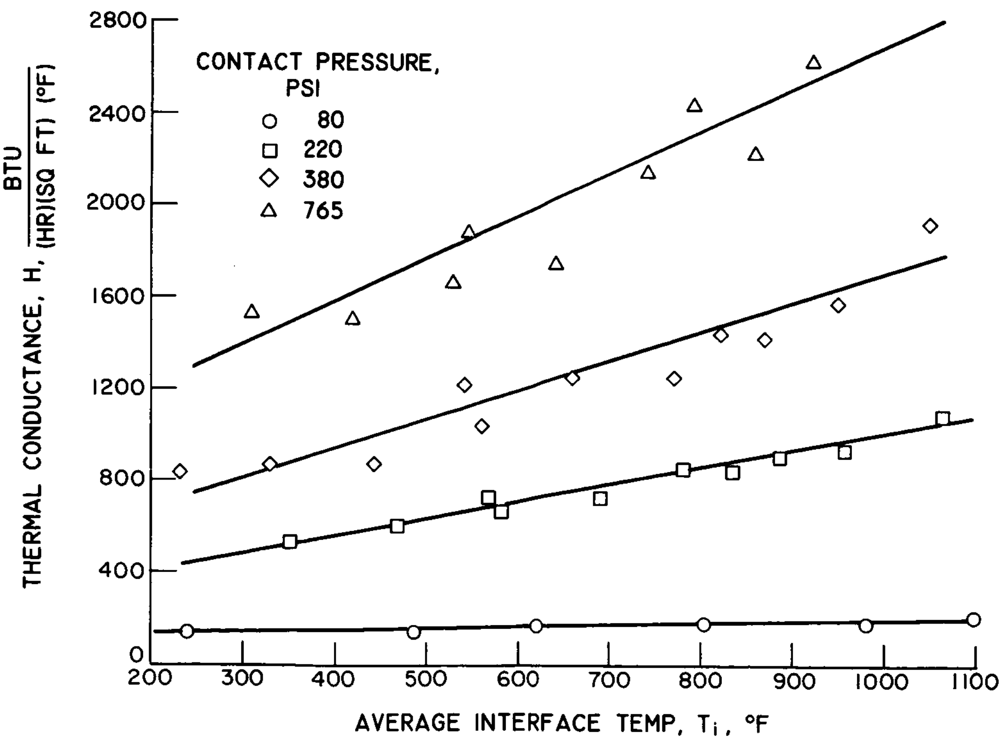

Fig. 6. - Thermal conductance of molybdenum-molybdenum. Ambient pressure, 10^{-6} Torr; surface roughness, 16 μin.

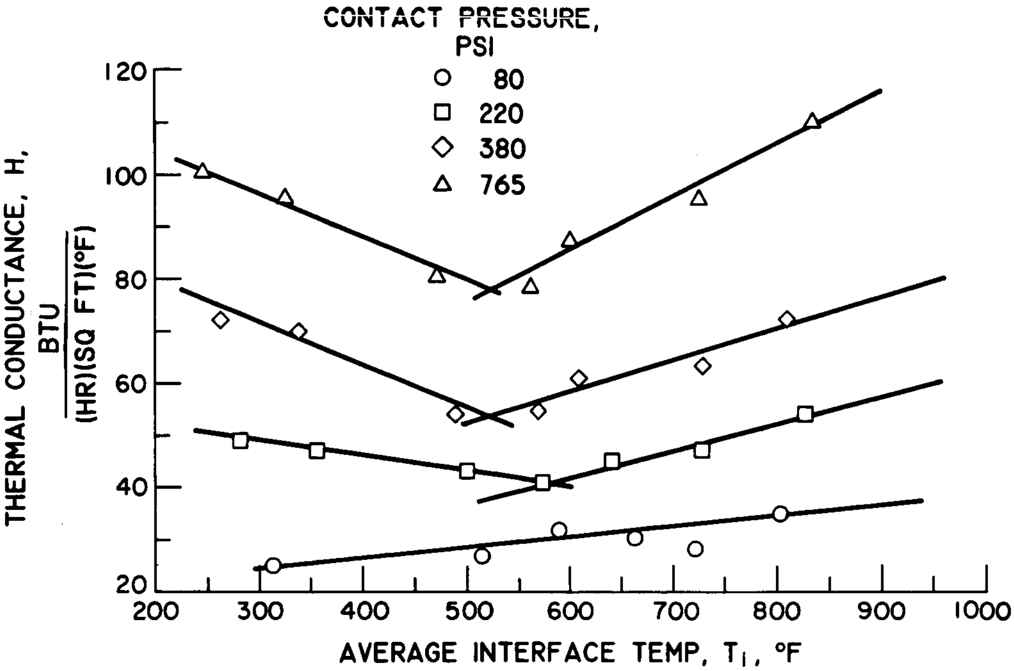

Fig. 7. - Thermal conductance of molybdenum-stainless steel 304 (heat flow from molybdenum to stainless steel 304). Ambient pressure, 10^{-6} Torr; surface roughness, 16 μin.

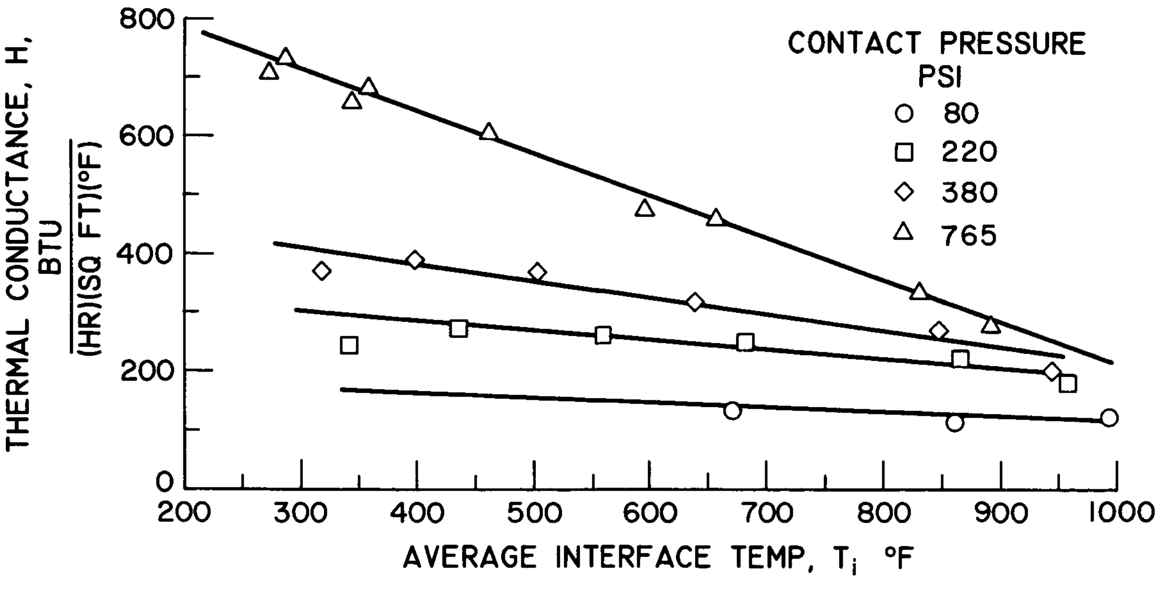

Fig. 8. - Thermal conductance of stainless steel 304 and molybdenmum heat flow from SS 304 to molybdenmum surface roughness 16μin.; ambient pressure 10^{-6} Torr.

E-2187